Detecting flux creep in superconducting $YBa_2Cu_3O_{7-\delta}$ thin films via damping of the oscillations of a levitating permanent magnet.

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The damping of the oscillations of a small permanent magnet (spherical shape, radius 0.1 mm) levitating between two parallel epitaxial YBCO films is measured as a function of oscillation amplitude and temperature. At small amplitudes the dissipation is found to be orders of magnitude lower than in bulk YBCO, Q-factors exceeding one million at low temperatures. With increasing amplitude the dissipation becomes exponentially large, exceeding the bulk values at large drives. We describe our results by calculating the ac shielding currents flowing through trapped flux whose motion gives rise to electric fields. We find dissipation to originate from different mechanisms of flux dynamics.

A permanent magnet levitating above, or suspending below, a superconducting surface has an equilibrium position which is determined by magnetic forces due to screening currents and trapped flux [1]. Except for a small logarithmic long-term relaxation of the magnetization of the superconductor this position is stable. The system is in a metastable state with stationary flux lines and consequently without any decay of the dc supercurrents, i.e., without any energy dissipation. However, oscillations of the levitating magnet about its equilibrium position give rise to ac magnetic fields at the surface of the superconductor which modulate the shielding currents. The initial state is now disturbed. The superconductor periodically tries to relax to more favorable metastable states by moving flux lines back and forth as a result of the oscillating component of the Lorentz forces. This leads to energy dissipation which we can determine from measurements of the oscillation amplitude of the magnet as a function of an external driving force.

In our present work we have investigated the energy dissipation when the magnet is levitating between two horizontal $YBa_2Cu_3O_{7-\delta}$ (YBCO) epitaxial thin films. We find that at small amplitudes and low temperatures the damping is several orders of magnitude smaller than with YBCO bulk samples studied in earlier work [2], leading to Q-factors above 10^6. This result may be of significance when application of superconducting levitation, e.g., for micromechanical bearings, is considered [1]. At large driving forces and at temperatures above 77 K, however, the dissipation grows exponentially with the oscillation amplitude and ultimately even exceeds the bulk values. We discuss our results in terms of thermally activated flux flow phenomena in the superconducting films.

Our experimental method has been described in detail in earlier work on sintered YBCO [2], or niobium [3], and also when using the oscillating spherical magnet for hydrodynamic experiments in superfluid helium [4]. It consists of placing a magnetic microsphere made of $SmCo_5$ (radius 0.1 mm) inside of a parallel plate capacitor (spacing $d = 1$ mm, diameter 4 mm) having electrodes which in our present work are made of YBCO epitaxial thin films (thickness $\delta = 450$ nm and in a second experiment 190 nm) laser deposited on insulating substrates [5]. We prepared the YBCO films on $SrTiO_3$ (lower electrode) and Y_2O_3-stabilized ZrO_2 (upper electrode) substrates cut with an inclination of 2 degrees off the (001) orientation. The inclination improves both flux pinning and, due to initiating a terrace growth, crystallinity of the films. The lower electrode is protected by a 20 nm thick $PrBa_2Cu_3O_7$ epitaxial layer. The YBCO films have an extremely sharp superconducting transition at $T_c = 89.5$ K measured by an ac susceptibility method, the complete transition width being 0.1 K. Before the capacitor is cooled through T_c we apply a dc voltage of about 800 V to the bottom electrode. Therefore, the magnet carries an electric charge q of about 2 pC when levitating. The dc voltage is then switched off and oscillations of the magnet can be excited with an ac voltage U_{ac} ranging typically from 0.1 mV to 20 V and having a frequency at the resonance of the oscillations (≈ 300 Hz). These vertical oscillations induce a current qv/d in the electrodes, where v is the velocity of the magnet, which is measured by an electrometer connected to a lock-in amplifier. For a given driving force $F = qU_{ac}/d$ we measure the maximum signal when slowly sweeping the frequency towards resonance. We then vary the driving force at constant temperature. In order to infer the velocity amplitude from the measured current amplitude and the driving force from the ac voltage we determine the charge q by recording a resonance curve and analyzing its width (which is given by the damping coefficient) and its height which then determines the charge. The driving forces range from 10^{-13} N to 10^{-7} N, the velocity amplitudes from 0.1 mm/s to 50 mm/s, and the oscillation amplitudes $a = v/\omega$ from 50 nm to 30 μm. The dissipated power varies from 10^{-9} W down to below

10^{-17} W which is less than what is usually dissipated when investigating flux creep by measuring the ac susceptibility or the current-voltage characteristic of a type II superconductor.

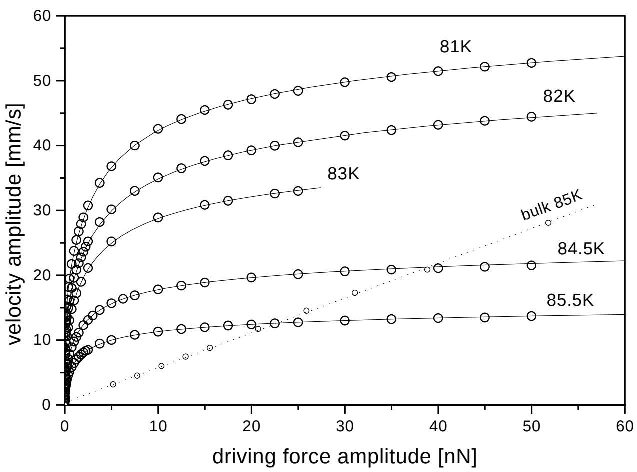

FIG. 1. Resonant velocity amplitude of the oscillating magnet as a function of the driving force at various temperatures. Note the steep increase at small driving forces and a logarithmic dependence at large drives. The lines are fits of our model to the data, see text. A typical linear dependence observed with melt-textured bulk samples is shown for comparison.

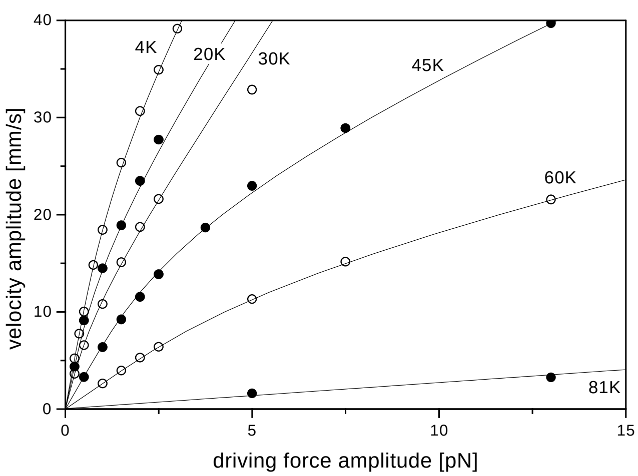

FIG. 2. Velocity amplitude at very small driving forces indicating the linear initial increase at various temperatures. The lines are fits of our model to the data, see text.

A summary of our data obtained with the 450 nm films above 77 K is shown in Fig. 1. At small driving forces we find a steep initial increase of the velocity amplitude of the magnet, whereas at driving forces above ca. 10 nN there is only a logarithmic dependence. This implies an exponential increase of the dissipation. At lower temperatures this logarithmic regime could not be reached because the oscillations became unstable at large amplitudes. The small-signal behavior is shown in Fig. 2 with a largely expanded abscissa. Only at very small amplitudes we do find a linear regime between the driving force amplitude F and the velocity amplitude v, i.e., $F = \gamma v$ with a strongly temperature dependent coefficient $\gamma(T)$, see Fig. 3. While γ decreases considerably below the critical temperature T_c, it obviously levels off at 4 K. Here the Q-factor $m\omega/\gamma$ ($m = 5.2 \cdot 10^{-8}$ kg is the mass of the magnet) exceeds 10^6 [6]. The steep drop below T_c follows approximately a $(T_c - T)^{-2}$ law as can be seen in the insert of Fig. 3. Comparing these results with our data on bulk YBCO [2] we note that at 78 K γ has decreased by three orders of magnitude.

For a more quantitative analysis we first calculate the sheet current on the surface of the superconductor by assuming that the magnetic field on either surface is given by the dipolar fields of the magnet and the first image dipole, neglecting images further away and also modifications of the field due to trapped flux lines. From the remanence of the magnet and its radius we calculate its magnetic moment to be $4 \cdot 10^{-6}$ Am^2. We further assume that the magnet levitates in the middle between the electrodes, i.e. at a height $h = h_0 = 0.5$ mm [7]. It is simple to calculate the dc sheet current on the surface for a particular orientation of the dipole with respect to the surface [8]. The orientation of the dipole parallel to the surface has the lowest energy but because of trapped flux we cannot rule out that some other orientation applies. Although the variation of the surface current $\vec{J} = (J_x(x, y, h_0), J_y(x, y, h_0))$ (x and y are coordinates on the surface) is quite complex and changes drastically with the orientation of the dipole, the maximum value J_{max} is fairly insensitive to the orientation: $J_{max} = 4400$ A/m when the dipole is perpendicular and $J_{max} = 5100$ A/m for the parallel orientation. In either case the magnetic field is below H_{c1}, but some flux remains trapped because we have a field-cooled situation. We then calculate the ac sheet current $\Delta\vec{J}$ due to the oscillations of the magnet about its position at h_0:

$$\Delta\vec{J}(x, y, t) = \left(\left(\frac{\partial J_x}{\partial h}\right)_{h_0}, \left(\frac{\partial J_y}{\partial h}\right)_{h_0} \right) a \cos(\omega t), \quad (1)$$

where a is the oscillation amplitude. Again the current distribution is complicated but the maximum amplitude of ΔJ is insensitive to the orientation of the dipole. An oscillation amplitude $a = 0.5$ μm corresponding to a velocity amplitude of $v \approx 1$ mm/s leads to a maximum current amplitude of 14 A/m for the perpendicular orientation and of 15 A/m for the parallel one. The current is localized in a small area of the superconducting surfaces below and above the sphere. This ac sheet current is actually an oscillating current density j in the film which exerts an oscillating Lorentz force on the trapped flux lines. Some flux lines will be set into motion thereby creating an electric field $E = v_{\rm f} n \Phi_0$, where $v_{\rm f}$ is the flux

line velocity and n is the number of flux lines per area. Because j and E are parallel the dissipation per unit volume is given by $j \cdot E$. If, for simplicity, we use an average current density $\langle j \rangle$ inside the film of thickness δ, we can describe the dissipation per unit area by $\Delta J \cdot E$, where E depends on $\langle j \rangle = \Delta J/\delta$ [9]. We can calculate the stationary oscillation amplitude at resonance by employing the energy balance between the gain from the driving force and the loss per cycle (period τ):

$$\int_0^\tau F \cdot v \, dt = \int_0^\tau \int_{x,y} \Delta J \cdot E \, dx dy dt \qquad (2)$$

In the linear regime $F = \gamma v$ the loss (r.h.s. of Eq. 2) can be described by a surface resistance $R_s \propto \gamma$, namely

$$\int_0^\tau \int_{x,y} R_s \cdot (\Delta J)^2 \, dx dy dt = R_s \int_0^\tau \int_{x,y} (\Delta J)^2 \, dx dy dt. \qquad (3)$$

In Fig. 3 the R_s values are given for the parallel orientation of the dipole [10]. From the surface resistance we can infer the imaginary part of the penetration depth of the ac field being given by $\lambda'' = R_s/\mu_0\omega$. In our case ($\omega/2\pi \approx 300$ Hz) we find λ'' to drop from 84 nm at 85 K down to only 0.2 nm at 4 K. While at present we do not have a model for a quantitative analysis of these data, we note that a steep decrease of the surface resistance with temperature is also observed at both radio and microwave frequencies and is believed to be due to small oscillations of the trapped flux lines or, in zero field, due to normal fluid electrons.

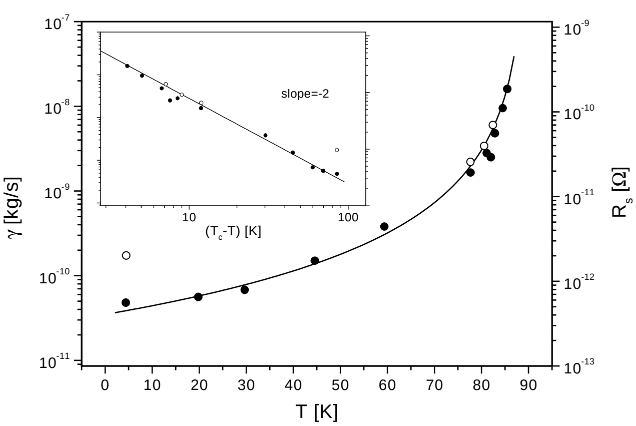

FIG. 3. Linear coefficient $\gamma = F/v$ from Fig. 2. Insert: same data (ordinate unchanged) plotted vs $T_c - T$. The surface resistance is calculated from Eq. 3. Open symbols are data obtained with the thinner film $\delta = 190$nm

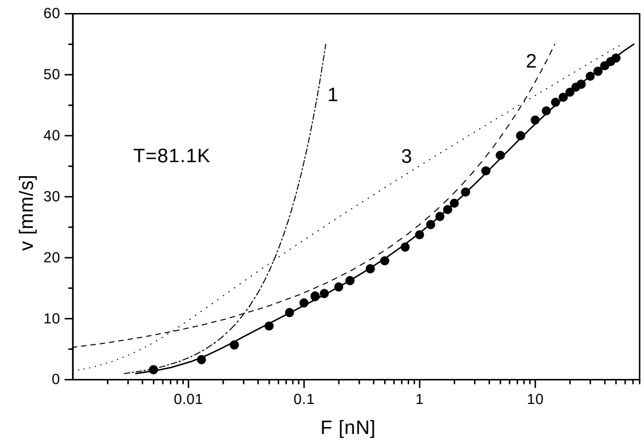

FIG. 4. Fit of Eq. 2 to a typical curve of Fig. 1. Indicated are the separate contributions of three different mechanisms of dissipation: 1 is the linear one (which is an exponential curve because of the logarithmic abscissa), 2 is the contribution from Eq. 4, and 3 is from Eq. 5. The solid line is the sum of these contributions.

In the nonlinear regime of $v(F)$ the electric field in Eq. 2 must have a nonlinear current dependence. This is usually described by thermally activated flux motion $v_{\mathrm{f}} \propto \exp(-U(j)/kT)$ with current dependent pinning energies $U(j)$, for a review see [11]. Essentially two different dependences are being considered, firstly barriers diverging for $j \to 0$:

$$U(j) = U_0 \left(\frac{j_0}{j} \right)^\mu , \qquad (4)$$

where $j \leq j_0$ and $0 < \mu < 1$. Vortex glass and collective creep models (for the latter ones $\mu > 1$ is also possible) yield this behavior which implies zero dissipation in the limit $j \to 0$. Secondly, for large currents, one considers barriers vanishing at a critical current density j_c as

$$U(j) = U_0 \left(1 - \frac{j}{j_c} \right) , \qquad (5)$$

which leads to an exponential dissipation for large currents (Kim-Anderson model), $E \propto \sinh(j/j_1)$ with $j_1 = j_c kT/U_0$. We fit the complete $v(F)$ curves by including both nonlinear mechanisms (Eqs. 4, 5) and a linear term additively in the energy balance, see Eq. 2. An example is shown in Fig. 4, where the separate contributions and their sum are compared with an experimental curve. The linear term contributes only at very low amplitudes. In the intermediate range the glass (or creep) term (Eq. 4 with $\mu = 0.2$) is dominant. Only at the largest amplitudes the Kim-Anderson term (Eq. 5) becomes relevant. It is this mechanism which leads to the observed slow logarithmic increase of the oscillation amplitudes at large drives in Fig. 1. Towards lower temperatures only the linear term and the glass term contribute as no data could be obtained at larger drives because the oscillations became unstable. From these fits we can

determine the barriers $U(j)$ at various temperatures, see Fig. 5. It is a peculiarity of Eq. 5 that only the constant slope $-dU/dj = U_0/j_c$ can be obtained reliably from a fit to the data because the quantity U_0 determines only the prefactor which we do not evaluate for it contains other unknown quantities, e.g. the density of the trapped flux n or the prefactor of the vortex velocity $v_{\rm f}$. From Fig. 5 it is evident that at large currents and high temperatures the barriers of Eq. 5 ultimately drop below those of Eq. 4 [12]. It is interesting to note that all three mechanisms of dissipation are found to apply simultaneously and additively. We do not find any indication of a sudden disappearance of one of the mechanisms which might be caused by a phase transition in the vortex system. In this context it may be important to remember that we are dealing with a low vortex density. We do find, however, that the critical current j_c in Eq. 5 extrapolates to zero at 86.5 K (well below T_c = 89.5 K) which might indicate an onset of free flux flow where the magnet loses its lateral stability.

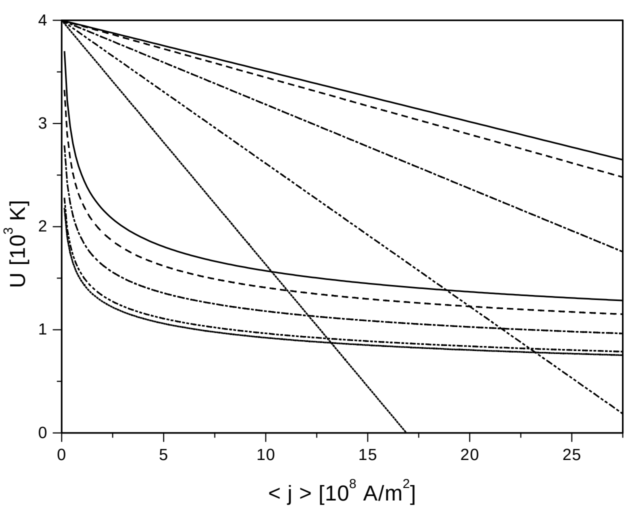

FIG. 5. Dependence of the pinning potential U on the average current density in the film obtained from the fits of our model to the data: curved lines are Eq. 4, straight lines are Eq. 5 at the following temperatures (from top to bottom): 78 K, 81 K, 83 K, 84.5 K, 85.5 K. Note that from Eq. 5 we can determine only the slopes U_0/j_c, in the figure we arbitrarily set $U_0 = 4 \cdot 10^3$K

In summary, our method of studying the dynamic properties of a levitating magnet yields results on flux pinning which are supplementary to those of the more standard techniques like measurements of the ac susceptibility, magnetic relaxation, or current-voltage characteristic. Because of the dipolar magnetic field the analysis of the results may be more complicated but our method has the advantage of being independent of edge effects and demagnetization factors. The enormous increase of the losses in the YBCO films from a very low level to an exponential dissipation is a surprise and is in sharp contrast to bulk samples. A more detailed account of our experiments including an analysis of the results on bulk samples (sintered and melt-textured) and of the elastic properties of the oscillating magnet will be presented elsewhere.

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[6] The Q-factor is still low enough to neglect dissipation by the input impedance of the electrometer or by residual gas (the cell was evacuated and contained charcoal for cryopumping). Eddy current losses in normal conducting metal parts of the measuring cell are difficult to estimate but appear to be too small to limit the Q value at 4 K.

[7] At the end of the experiment the capacitor was heated above T_c and the magnet fell to the lower electrode. The change of the induced charge $q \cdot h_0/d$ was measured. From this we determine the levitation height to be $h_0 = (0.4 \pm 0.1)$ mm.

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[10] For the perpendicular orientation R_s would be smaller by a factor of 2. Note that different current distributions on the surfaces and a different magnetic moment of the sphere will change R_s.

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[12] Satisfactory fits could also be obtained using Eq. 4 with values of μ up to 0.6. This, however, leads to barriers comparable to kT for our measuring currents, which appears unreasonable.